Autopilot Studies for Turbulence Ride Smoothing

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Outline of Presentation

- Background
- Problem Description (Why This is Hard)
- Possible Approaches
- Some Possible Criteria for Success
- Some Results / Status
- Conclusions and Recommendations

Background

•1991-93	Boeing Military Airplanes – Use of Forward-Looking Sensors for Gust Load Alleviation
•1993-98	HSR/HSCT – Gust Load Alleviation/Ride Comfort
•1998-present	Boeing IR&D Studies
•1999-2000	NASA Contract Study – Forward-Looking Sensor/Open Loop Aircraft – Safety Enhancement
•2001-2002	NASA Contract Study – Forward-Looking Sensor + Modified Autopilot – QSAE Aircraft
•2002-2003	NASA Contract Study – Linear Aeroservoelastic Model
•2003-2004	NASA Contract Study – Add Aeroelastic Model to Nonlinear Matlab/Simulink Model- Study “Zero-Look” Sensors + Autopilot Modifications

Problem Description (Why This is Hard!)

•Aircraft responds to vertical turbulence in both plunge (mostly) and pitch (makes the aft end worse). Traditional “Attitude Hold” approach decreases pitch but may increase plunge.

•Plunge response (Nz) is a direct response to the gust input (direct feed-through term in the D-Matrix). Most turbulence accidents exhibit large negative Nz. “Altitude Hold” (and usually the pilot’s response) makes it worse.

•Elevator Control is indirect, because:

- The ($Nz/\delta e$) transfer function is non-minimum phase.
- There is a zero in the right-half plane.
- When the elevator is deflected, the airplane goes the wrong way!

Possible Approaches

Inverse Control Using Elevator:
- Aircraft response to gust - (Nz/Wg)
- Aircraft response to control - ($Nz/\delta e$)
- Control Law should be – $(\delta e/Wg) = (Nz/\delta e)^{-1} * (Nz/Wg)$, right?

Wrong! (That pesky non-minimum phase r.h.s. zero in $Nz/\delta e$.)

Direct Lift:
- Use of Spoilers and Trailing Edge Surfaces (symmetrically).
- ($Nz/\delta f$) is minimum phase (airplane goes the right way). But…
- Some current airplanes (747,767,777) don't have large enough inboard high-speed flaperons, most (737,757) don't have any.
- Outboard ailerons are (mostly) washed-out at cruise due to aeroelastic effects, and have large pitching moment.
- Spoilers only go one way (wrong way for the Safety Problem).

Possible Approaches (Continued)

•Use of Feed-forward Control:

- Definitions: Feedback – airplane response → control surface
  Feed-forward – measured input → control surface

•Feed-forward control allows time to "anticipate", i.e. elevator can be used to "fly the gust," creating positive lift due to pitch at <u>the right time</u> to counteract negative gust (or vice versa). Elevator affects the short period and requires time to respond.

•Studies have shown that 0.5 to 1.5 seconds "look-ahead" can provide significant reduction in Nz response (> 50%), and consequent large (> 80%) reduction in injuries, IF

•Sufficient control authority is available (deflection and rate) for large (injury-causing) gusts.

Possible Approaches (Continued)

However:

•Forward-looking sensors which can map the gust field (e.g. scanning or multi-beam lidar) are not expected to be in production for several years. A "detector" (lidar or radar) could be available significantly earlier, but longer range lidar for warning requires much higher power, size, weight.

•Non-fly by wire airplanes (most of them) can only input commands to the elevator through the autopilot servos.

•Because of structural limits due to potential hard-over or oscillatory failure, single-channel autopilot authority is very limited, e.g. to approximately +/-3 degrees and 19 deg/sec for 757-200 at cruise conditions. (PCU is ~ +/- 15 deg, 45 deg/sec)

Possible Approaches (Continued)

So:

•Current study has concentrated on "near-zero look-ahead" solutions, i.e. using existing "on-board" sensors to estimate the gust, assuming a "switch-on" (manual or automatic threshold detector) is available, together with -

•Adding forward-feed to the existing autopilot control laws, and

•What could be accomplished if "triple channel" autopilot authority (- 25/+15 deg elevator) and redundancy, along with higher autopilot servo rates, were available.

•Currently, "triple channel" is only available during autoland, but alternate modes of engagement are being studied.

Possible Criteria for Success

- A large data base of documented turbulence accidents/ incidents has been reviewed:

  - From 1/1/83 to 4/10/04:

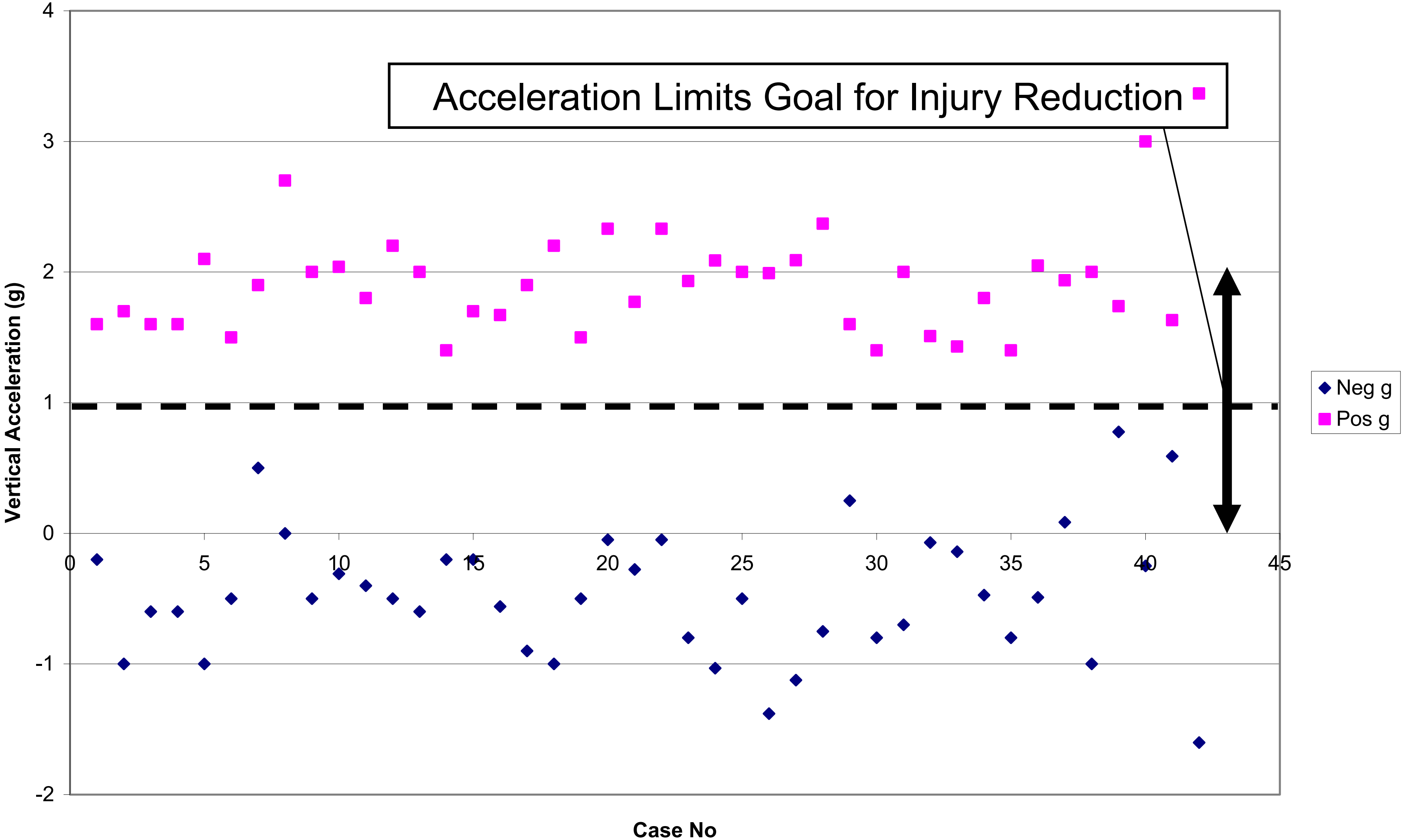
    232 Accidents 97 Incidents (reported)

    2368 Injuries to PAX and FA

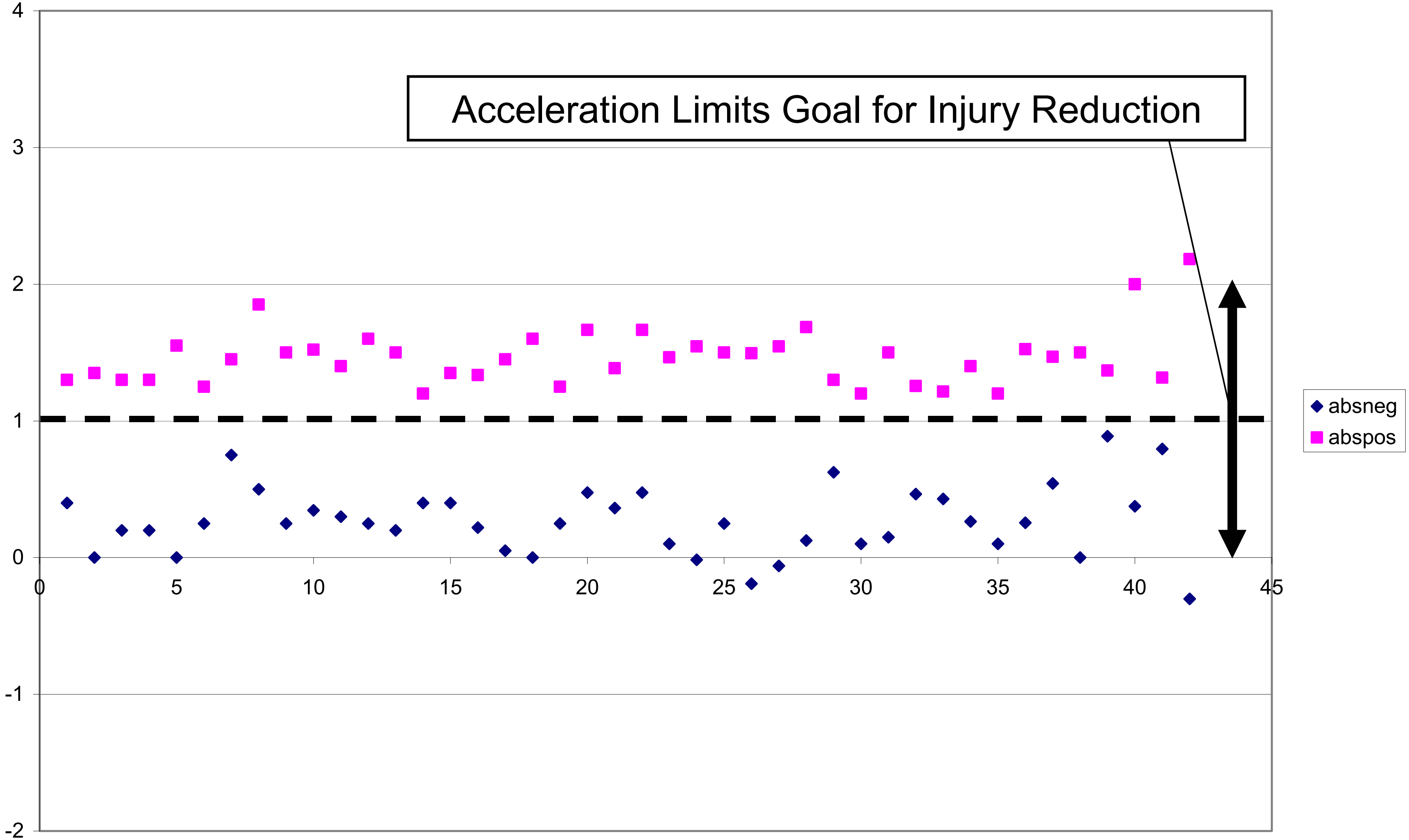
    ~ 42 cases have Pos. and Neg. Nz (max) from FDR available. 88% have Nz < 0 g.

    ~ 15 case have FDR data traces available

Peak Accelerations in Turbulence Injury Accidents



50% Peak acceleration reduction



Possible Criteria for Success (Cont'd)

C.G. Acceleration to Reduce Turbulence Injuries

Acceleration Reduction	Percent Injury Reduction
25%	~35%
50%	~80%

Possible Criteria for Success (Cont'd)

However:

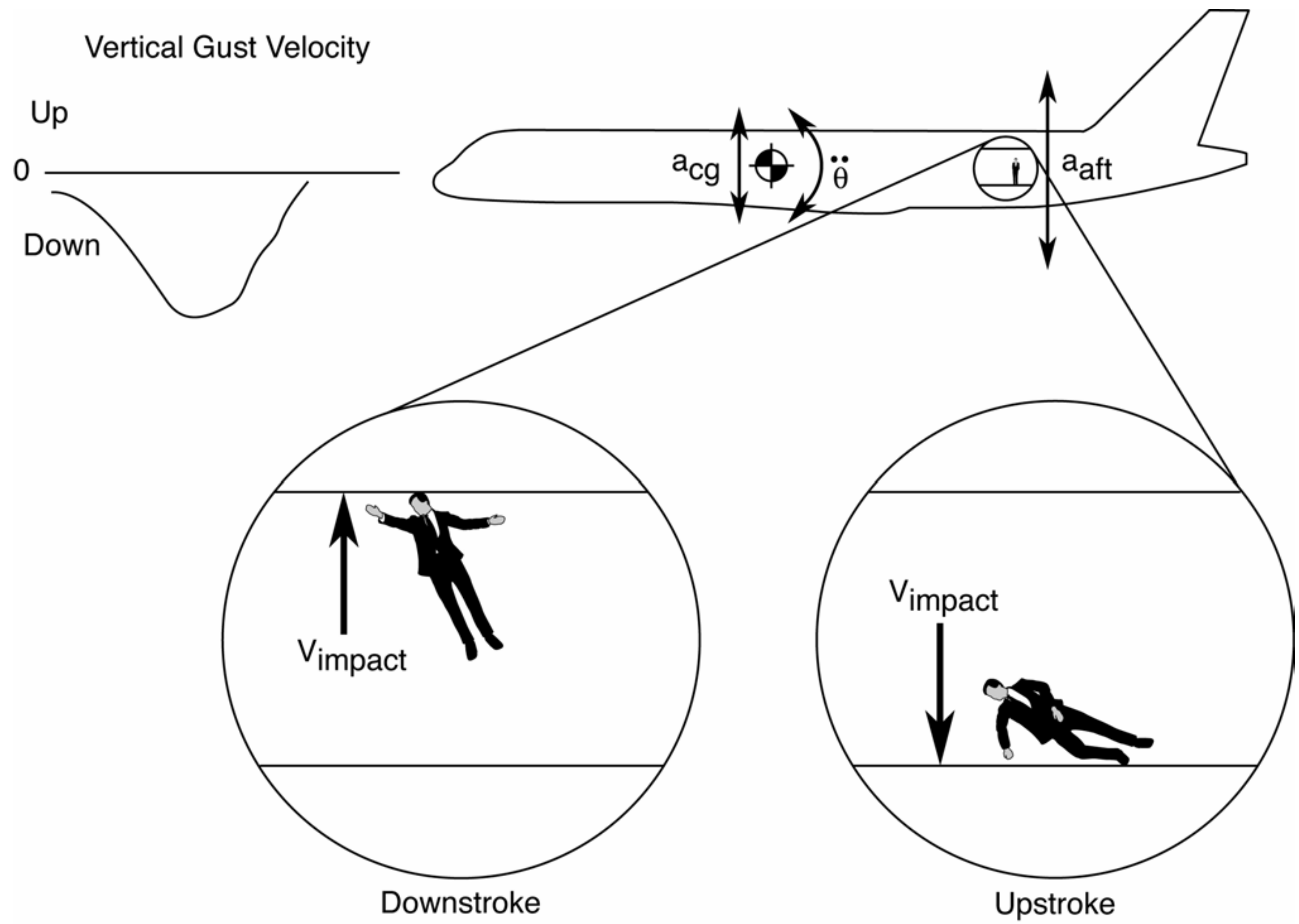
•Without direct lift or forward-looking sensors it is very difficult to reach 50% acceleration reduction (~ > 0 g's).

•An alternate approach is to reduce "equivalent fall height" (EFH), i.e. how far the unrestrained PAX/FA would "fall" (down or up) in a 1-g environment, based on equivalent impact velocity.

•HF studies have shown that multiple serious injuries occur for falls > 5 ft. Non-aircraft (medical) data indicates serious injuries would be reduced if EFH < 5 ft.

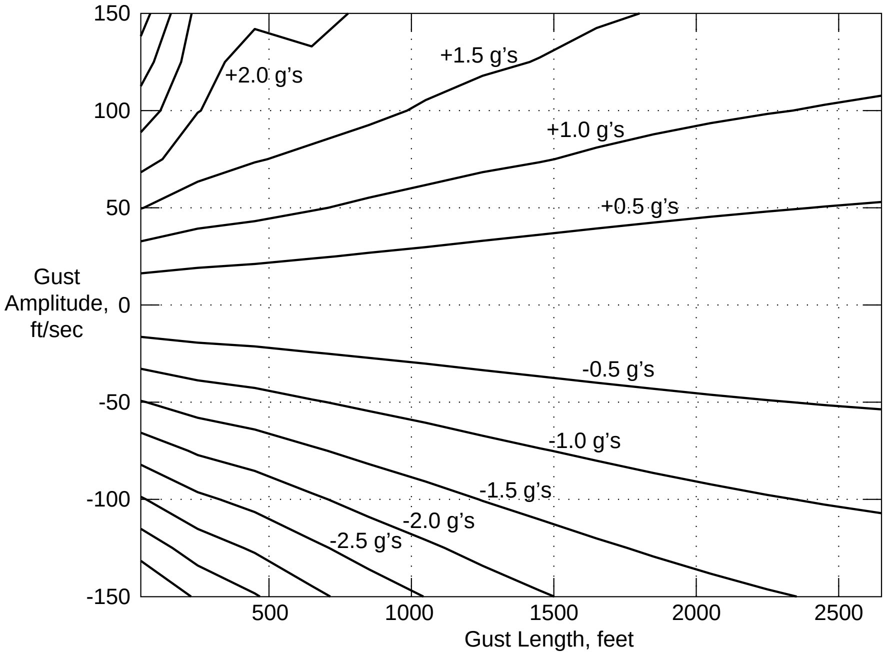
•EFH is <u>not</u> directly correlated with negative Nz, It depends on how fast the positive Nz "comes back".

Pax Impact with A/C Interior

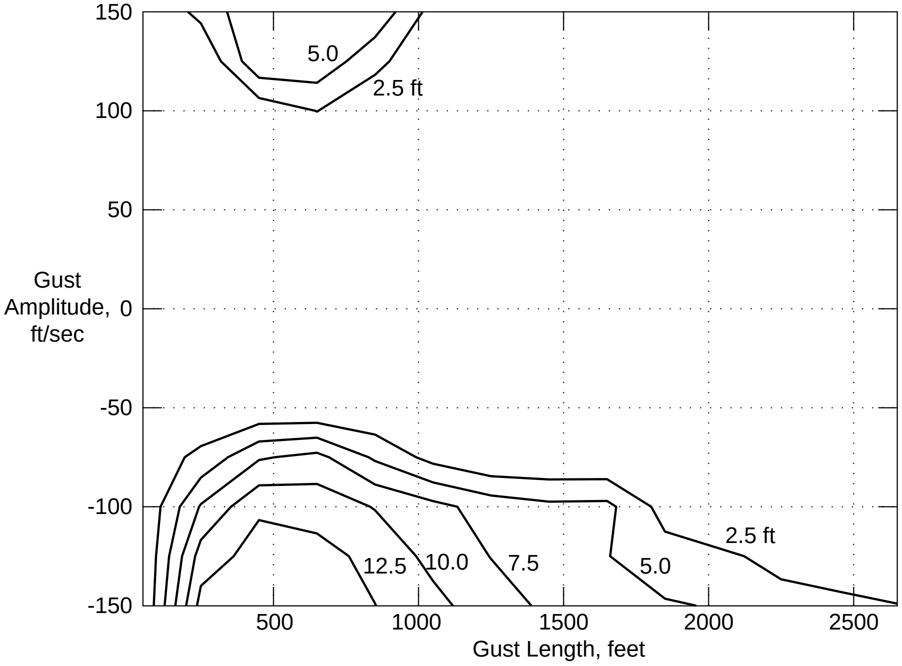


Effect of Gust Length (Frequency) and Gust Amplitude (1-cosine gust profile)

Acceleration



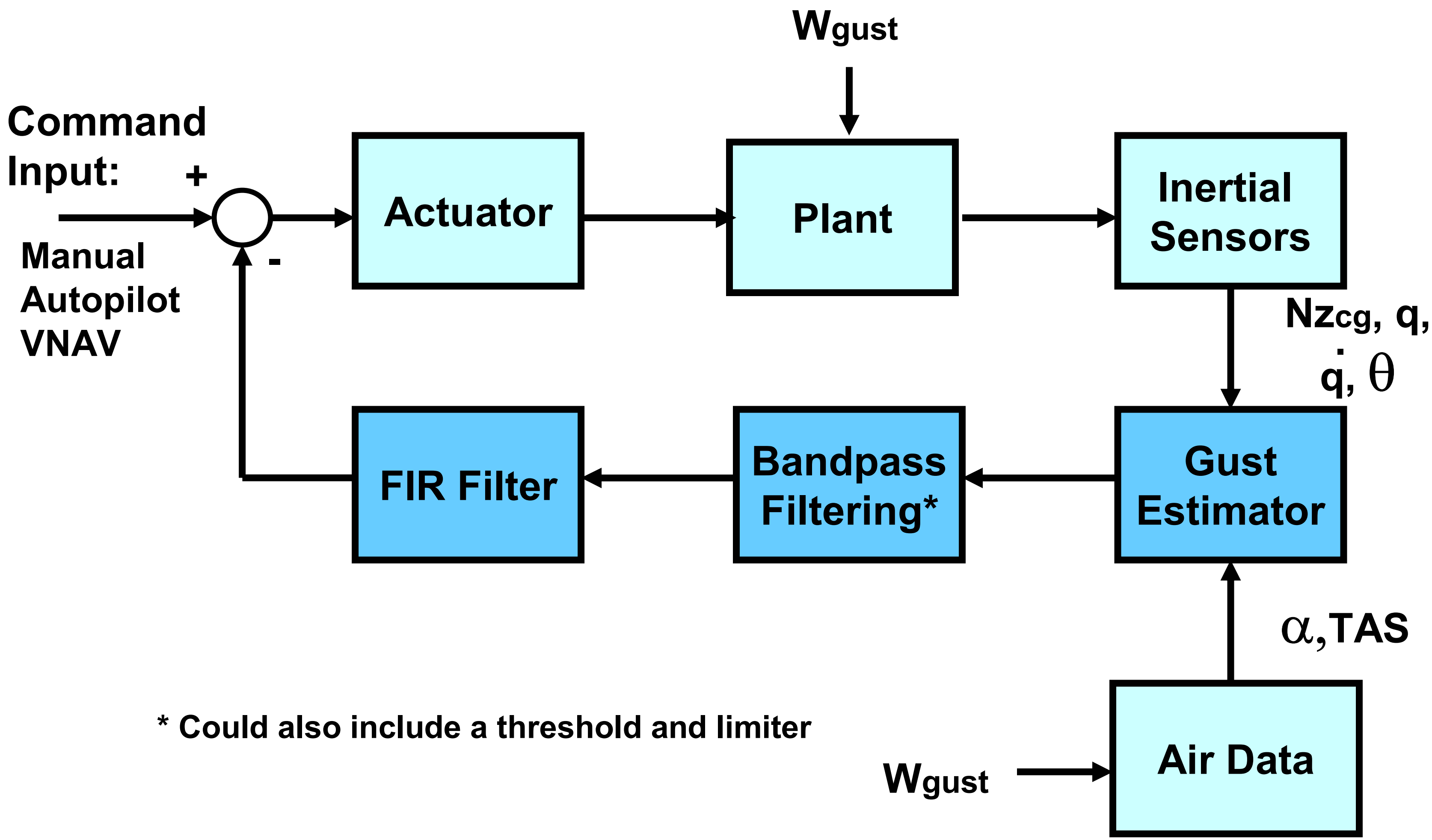
Equivalent Fall Height



Some Results / Status

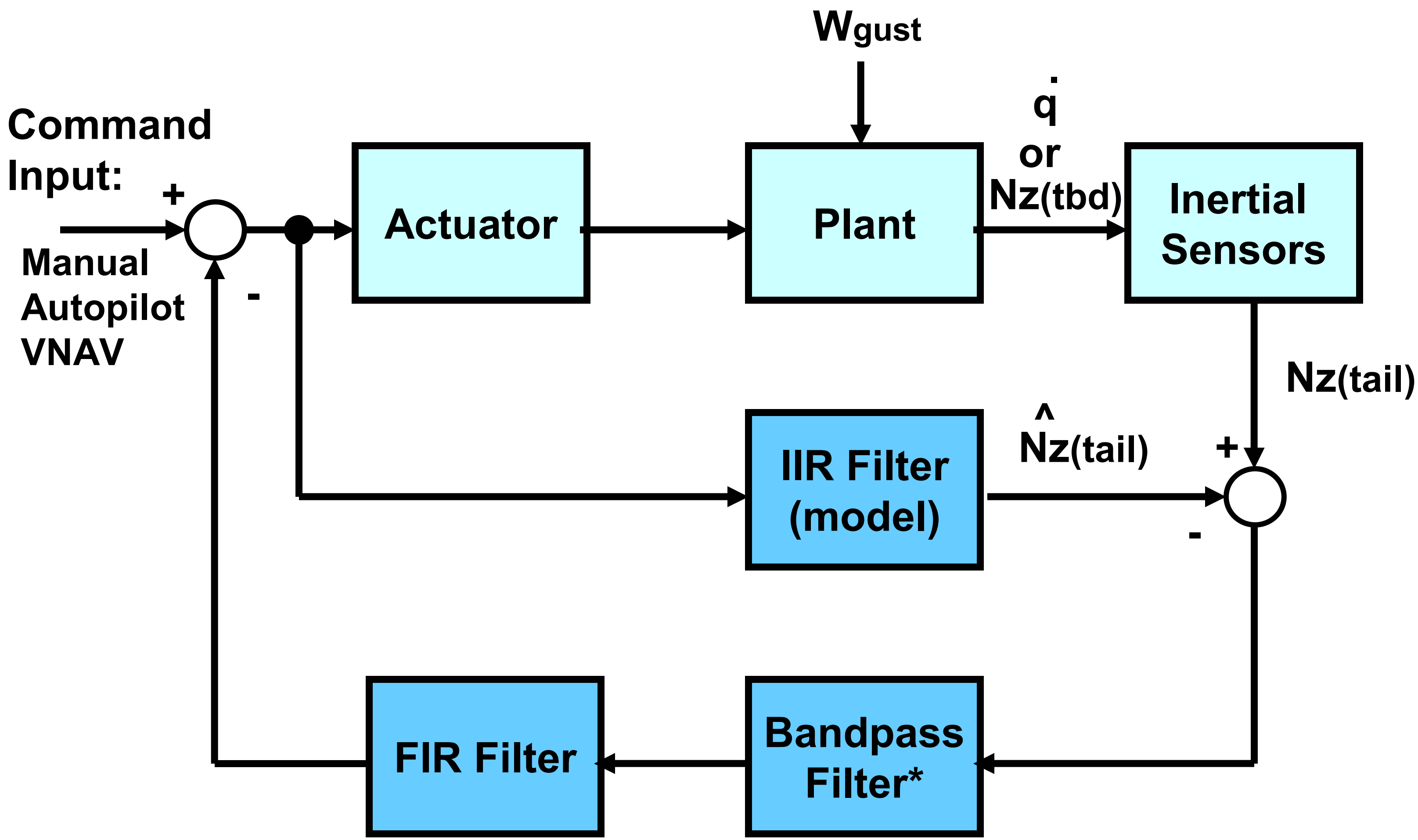
- Studies have been performed using QSAE and DASE models of 757-200 (linear and nonlinear simulation)
- Multiple control strategies have been examined:
  - Deconvolution
  - Two sided inverse z-transforms
  - Shannon/Bode realizable Weiner filtering
  - Linear Optimal Tracker
  - Linear Quadratic Regulator
  - Pole Placement
  - Scale factor with time advance
  - Adaptive Inverse Control - Offline
  - Adaptive Inverse Control/Model Following - Offline
  - Weighted Least Squares FIR Filter of gust input
  - Disturbance Canceling (FIR filtering in the feedback path)

Feed-Forward Control with Gust Estimation



* Could also include a threshold and limiter

Disturbance Cancellation Scheme



* Could also include a threshold and limiter

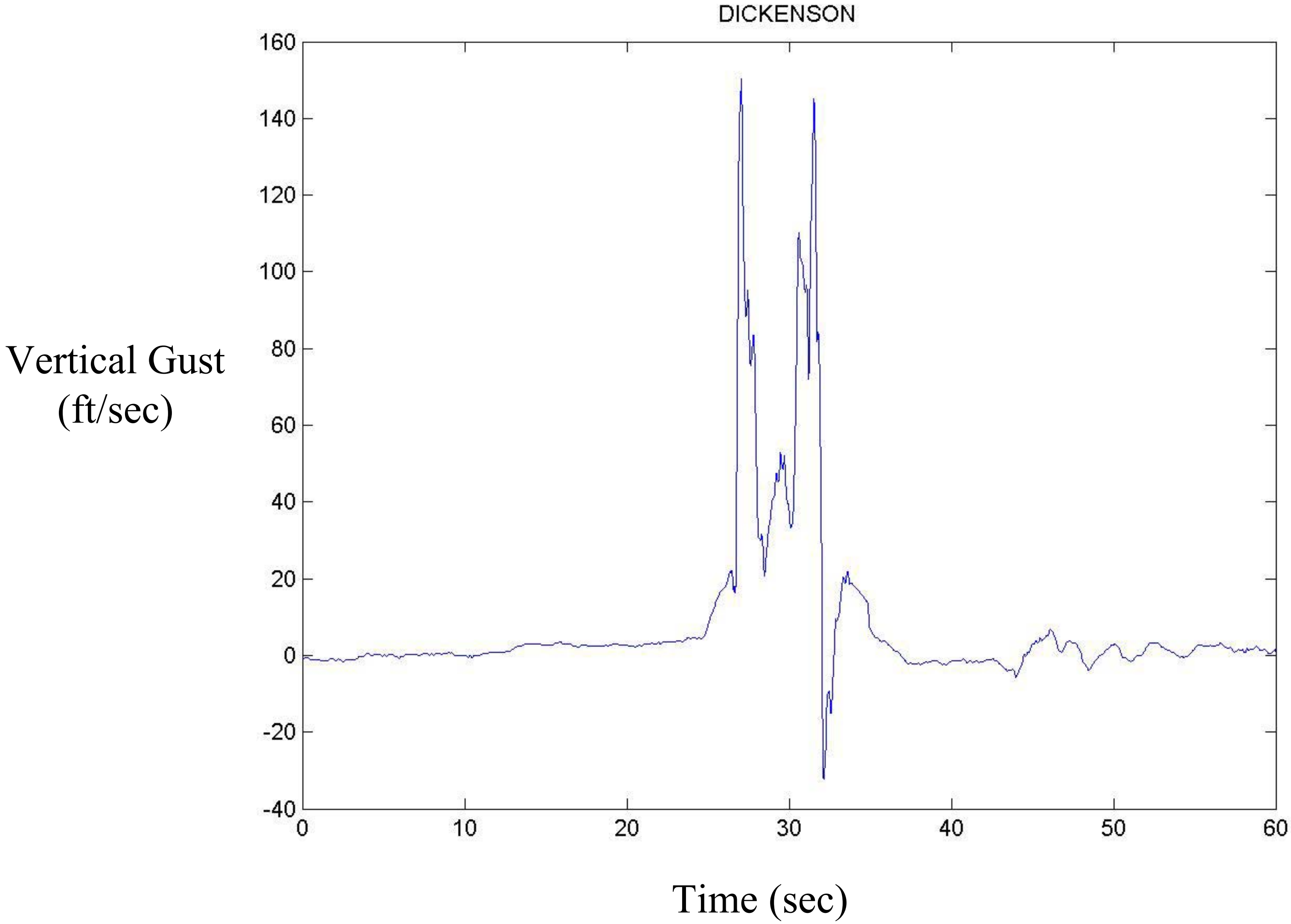
Some Results / Status (Cont'd)

•"Near-zero" and "forward-looking" schemes have been tested against a variety of theoretical and accident gust profiles:

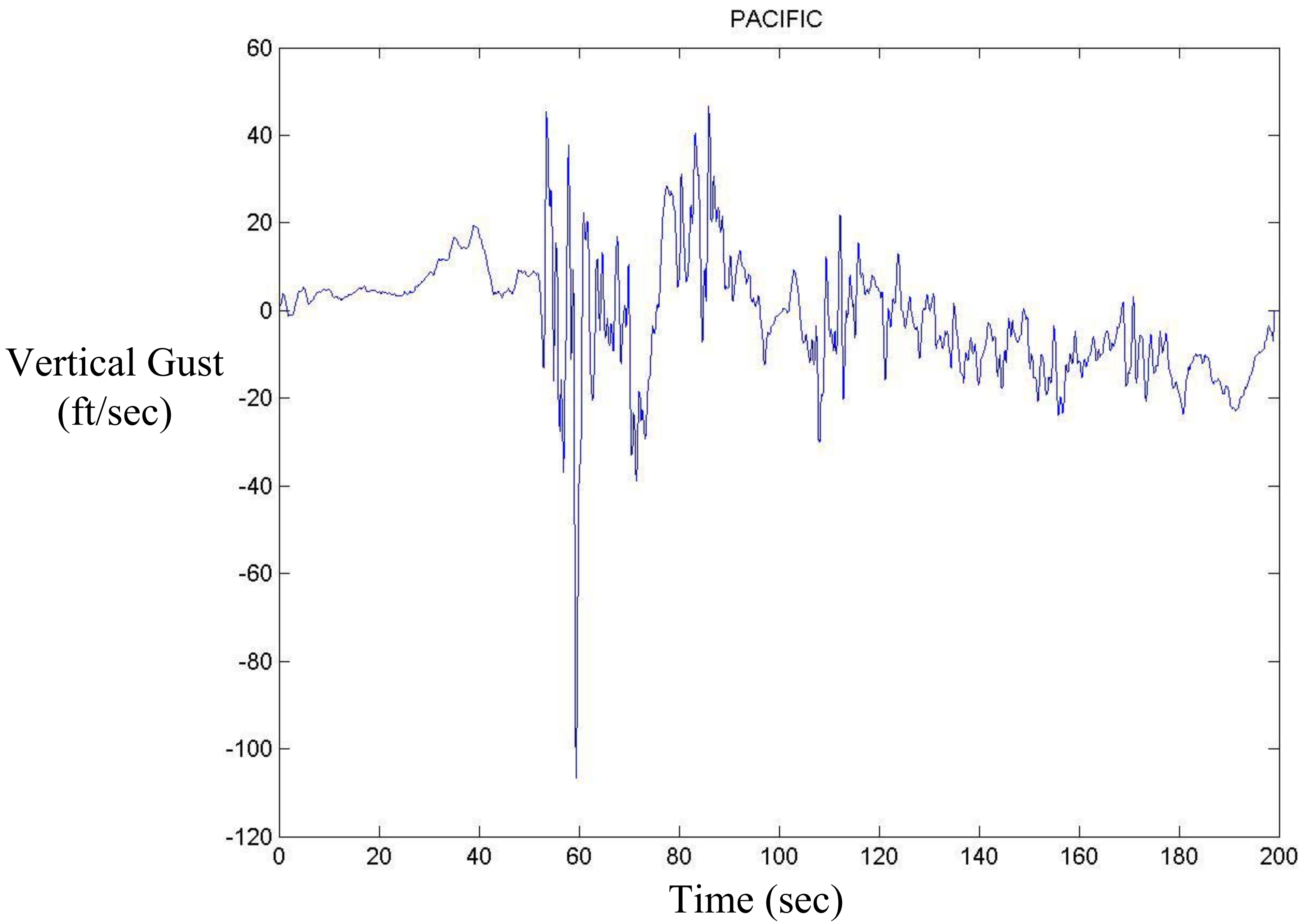
- Dryden turbulence
- 1 – cos
- Single and Multiple Vortex
- 5 Cases from Bach and Wingrove (NASA Ames)
- 3 Cases from Boeing Accident Investigation
- 2 Flight test cases from NASA Langley

•On-board sensors (α,q,θ,Nz) can be used for "near-zero" (100ms) look-ahead due to lag between gust at nose and the wing, and lift growth (appx 200 ms). Data rates ~ 20 Hz are required and sensor lags must be minimized.

Example – "Dickenson" Accident Profile

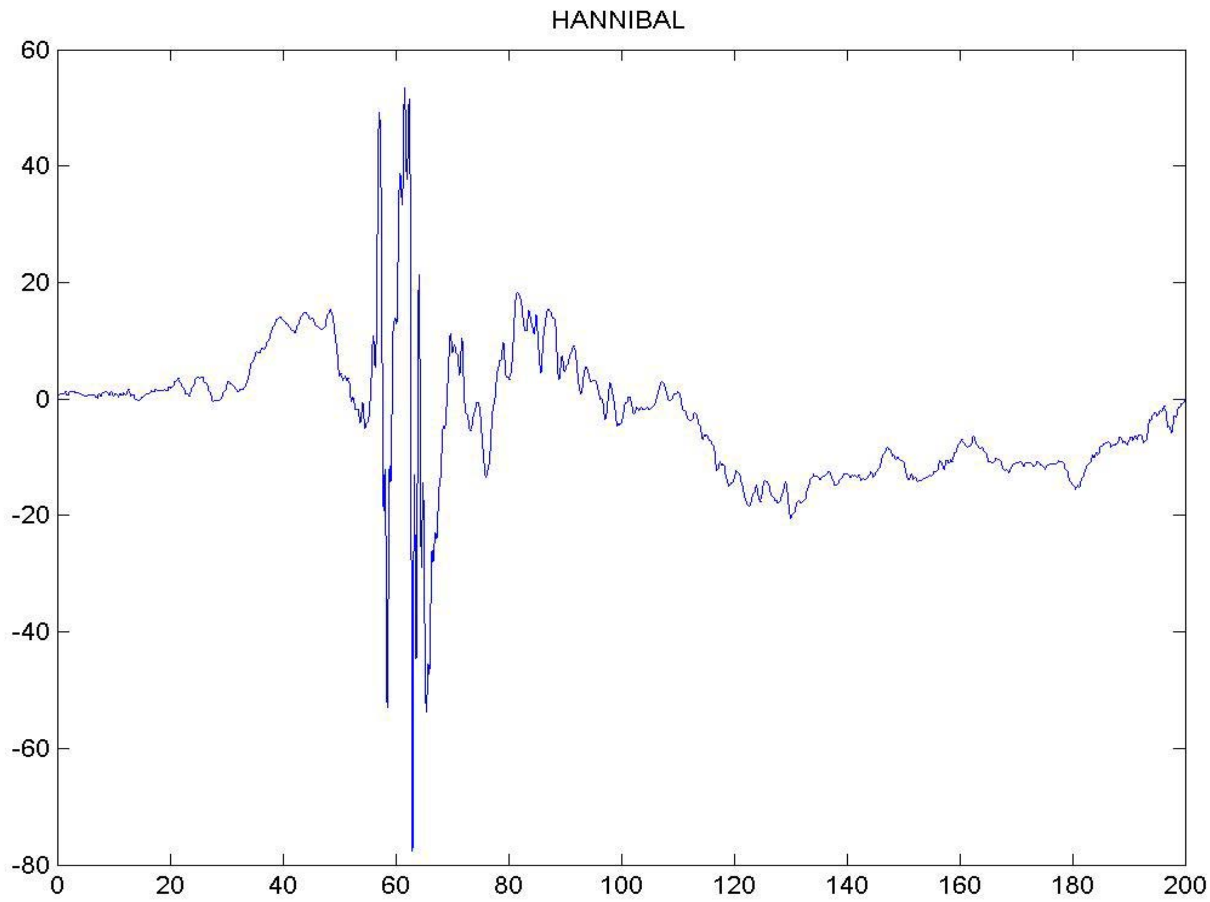


Example – "Pacific" Accident Profile



Example – “Hannibal” Accident Profile

Vertical Gust (ft/sec)



Time (sec)

Equivalent Fall Height (ft) Results

for "Near-Zero" Look-Ahead Control vs. Nominal Autopilot (Altitude Hold)

CASE	GUST PROFILE	ALT HOLD ONLY		ALT HOLD AND FFWD		ELEV DEFL	
		AFT	FWD	AFT	FWD	MAX	MIN
1	VORTEXN	8.33	6.63	4.29	5.01	7.48	-1.95
2	VORTEX_100P	8.38	6.64	4.93	4.69	9.42	-1.58
3	VORTEX_80P	8.66	6.63	4.91	5.29	8.37	-2.48
4	HANNIBAL	6.34	1.62	4.49	1.88	7.53	-2.55
5	DICKENSON	9.17	5.10	5.11	4.68	8.25	-8.21
6	GREENLAND	2.81	0.00	0.00	0.00	3.36	-4.86
7	BERMUDA	6.38	1.64	4.24	4.08	6.40	-2.03
8	CALGARY	0.00	0.00	0.00	0.00	1.48	-1.92
9	CHARLESTON	10.12	2.61	5.65	5.59	7.89	-7.32
10	191 - 06	1.82	0.00	1.69	0.00	4.91	-3.33
11	ATLANTIC	8.85	2.90	3.34	3.46	7.77	-2.99
12	PACIFIC	9.19	2.34	4.95	2.81	6.42	-3.62

Equivalent Fall Height (ft) Results
for 1.3 Sec Look-Ahead Control
vs. Nominal Autopilot (Altitude Hold)

CASE	GUST PROFILE	ALT HOLD ONLY		ALT HOLD AND FFWD+LA		ELEV DEFL	
		AFT	FWD	AFT	FWD	MAX	MIN
1	VORTEXN	8.33	6.63	0.00	0.00	6.78	-7.16
2	VORTEX_100P	8.38	6.64	0.00	1.31	9.40	-10.41
3	VORTEX_80P	8.66	6.63	4.79	2.57	12.76	-13.40
4	HANNIBAL	6.34	1.62	4.32	2.25	14.04	-9.04
5	DICKENSON	9.17	5.10	2.38	1.91	12.79	-16.02
6	GREENLAND	2.81	0.00	2.16	0.00	9.10	-10.96
7	BERMUDA	6.38	1.64	0.00	1.69	10.92	-4.91
8	CALGARY	0.00	0.00	0.00	0.00	4.69	-6.01
9	CHARLESTON	10.12	2.61	2.40	2.30	14.01	-13.99
10	191 - 06	1.82	0.00	2.44	0.00	5.94	-7.02
11	ATLANTIC	8.85	2.90	0.00	1.63	9.63	-5.93
12	PACIFIC	9.19	2.34	0.00	2.11	12.41	-7.61

Conclusions and Recommendations

•Modification of existing aircraft instrumentation and autopilot systems could provide a reduction in turbulence-related serious injury accidents.

- On-board instrumentation with high (~20 Hz) data rates and minimal lags to estimate the gust as hits the nose.
- Addition of forward-feed control to elevator when turbulence is predicted or detected (exceeds a threshold).
- Modification of autopilot logic and servo hardware to provide higher authority and redundancy (certification issue).

•Development, testing, production, and installation of forward-looking sensor to predict the gust 1-2 sec ahead of airplane (800-1500 ft) could practically eliminate serious turbulence injuries.